Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 105 (2015) 167 – 175
Procedia Engineering
www.elsevier.com/locate/procedia

6th BSME International Conference on Thermal Engineering (ICTE 2014)

Experimental investigation of transient heat transfer on a solid surface, with fire retardant fabric under hot air impinging jet

A.K.M. Nazrul Islam[a,]*, Md. Ashraful Islam[a], Manabendra Saha[b]

[a]Department of Mechanical Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh
[b]Centre for Energy Technology, School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia

Abstract

This paper represents an experimental investigation of the transient heat transfer on a solid base plate (mimic to skin) covered by fire retardant fabric (Kevlar® 49), under hot air jet impingement. The study was carried out by a fabricated attachment with an axial flow wind tunnel for horizontal hot air jet impingement. The hot air jet was impinged on a vertical base plate at different velocities and temperatures. A set of experimental conditions was considered to understand the various heat transfer phenomenon. The hot air jet temperatures were 115 and 125 °C respectively and jet velocities were 12, 15, and 19 ms^{-1} respectively at the exit point of the nozzle. The surface temperatures of the solid base plate are used to calculate the heat flux, local heat transfer coefficient, and Nusselt numbers. The maximum heat transfer is found on base plate, whilst the maximum decrease of heat flux is observed on fire retardant fabric. This experimental model can enhance the understanding and insights of the heat transfer process through permeable fabric.

Peer-review under responsibility of organizing committee of the 6th BSME International Conference on Thermal Engineering (ICTE 2014)

Keywords: Heat transfer; jet impingement; fire retarding fabric; Nusselt number.

1. Introduction

Every year, a large number of people are injured even burnt in the whole world as a result of fire incident. Most often, high heat flux exposures in the industrial accident is severe. To rescue the people from fire and high heat

* Corresponding author. Tel. : +88-01752 881199
E-mail address: akmnazrul@gmail.com

Peer-review under responsibility of organizing committee of the 6th BSME International Conference on Thermal Engineering (ICTE 2014)
doi:10.1016/j.proeng.2015.05.053

exposure, fire personnel come forward to fight in the high heat flux environment. The realistic tests have become essential to determine how much thermal protection can provide to the fire workers after wearing the fire protective clothing [1]. Consequently, extensive research have been conducted for better understanding about the mechanisms involved in heat transfer through thin fibrous layers and the thermal performance of protective clothing has been a point of interest for several decades. In 1954, Perry [2] conducted a research on convective heat transfer to a plane surface from a hot gas jet and Chen [3] conducted a research on transient heat and moisture transfer through thermally irradiated cloth in 1959. Fire retardant fabric (FRF) properties has steadily improved over the years for designing and creating a new fire protective fabric in order to prevent and minimize tissue burns that result from the radiant energy produced by fire as well as from the localized contact flame exposure. However, their performance had not been studied systematically in details for the safe keeping of their users yet. The aims of the current work are to study in depth of protective clothing and test protocols which are used in the evaluation of materials, clothing and protective equipments. Despite the existence of numerous tests for evaluating fire protective/ flame retardant clothing, there are still many unanswered questions considering the heat transfer response. This investigation focuses on the experimental evaluation of transient heat transfer through thin fibrous layers from an impinging heated air jet. The goal is to broaden the understanding of the spatial heat transfer distribution of the solid plate as well as FRF.

NASA conducted a research [4] for the Apollo service module propulsion system to find out the transient heat transfer behavior in 1965. In the same year Gardon and Akfirat [5] did another research to find out the role of turbulence in heat transfer characteristics of impinging jets. They discussed about the local heat transfer and flow conditions. Mohanty and Tawfek [6], and Goldstein et al. [7] kept constant both of the flat plate and the air jet to generate steady state solutions. Mohanty and Tawfek [6] used heat flux sensors to obtain local heat transfer measurements of a round air jet impinging normal to a flat surface. Goldstein et al. [7] studied the distribution of recovery factor and local heat transfer for an impinging jet on a flat isothermal plate under steady state conditions. Ukponmwan [8] and Torvi [9] studied and provided review of some of the works done for comfort and flammability of the FRF including the work of the government industry research committee (GIRC) [10]. Stoll et al. [11-12] discussed about the analytical, mathematical techniques and experimental method of method to determine the thermal radiation exposure on skin as well as heat transfer through fabrics as related to thermal Injury. Torvi [13] developed a model to simulate the heat transfer for bench top testing apparatus. Torvi et al. [14] used flow visualization methods to study the heat transfer in horizontal air spaces between solid boundaries. Anguiano [15] performed a study on skin stimulant material by a vertical hot jet. Islam et al. [16] conducted an experimental study on a solid bare plate by horizontal hot jet. However the study is not sufficient to understand the real situation at cotton fabric (CF) as well as different jet temperatures and velocities. Although a considerable amount of research has been carried out, but more effective research is essential to investigate results on heat transfer of horizontal hot air jet impingement on a flat surface through FRF fibrous layer. Even though few studies which dealt with heat transfer of impinging jet, did not focus on local heat transfer characteristics. In this study, an experimental facility has been fabricated to find the transient heat transfer phenomena on a vertical bare solid plate.

2. Experimental setup

The experimental study has been carried out by a co-axial wind tunnel and a heating attachment to the wind tunnel. The overall length of the wind tunnel is 9.0 m. It consists of an axial flow fan unit, two settling chambers, two diffusers, a silencer and a nozzle which are shown in Fig. 1(a) - (b). The fan unit consists of three axial wooden aerofoil shape fans in the same series. The fan unit receives air through the butterfly valve and discharges it into the silencer of the flow duct. Flow from the silencer passes on to the settling chamber through a diffuser. The jet velocity of the nozzle is controlled by regulating control unit of the fan. The temperature of the jet is regulated by controlling the supply voltage of the heater. The whole setup is mounted on rigid frames of mild steel pipes and plates and these frames are securely fixed with the ground. At the tip of the second settling chamber, the diameter of the flow facility is reduced from 475 mm to 88.9 mm where the heating section is placed. The heating section consists of a round nozzle. After that a vertical flat plate is placed in-front of the nozzle. The heated air allowed to pass through the long settling chamber to the nozzle having a diameter of 25.4 mm. Air from the wind tunnel is passed through the entrance section, heating section and settling chamber. Detailed explanation of the facility can be found in the studies of Hasan [17]. For the present investigation, a nozzle diameter of 25.4 mm is used. The test has been performed for different jet velocities 12, 15, 19 m/s respectively. Seven K-Type (Ni-Cr/ Ni-Al) thermocouples are placed on the base plate to measure the temperatures. One thermocouple is placed at the stagnation point, and 3 others on both top and bottom side of the stagnation point. A wooden frame is used to hold the fabric and the base plate as per provisions outline in ASTM standard [18]. All temperature measurements were recorded by using Picosoft data acquisition system.

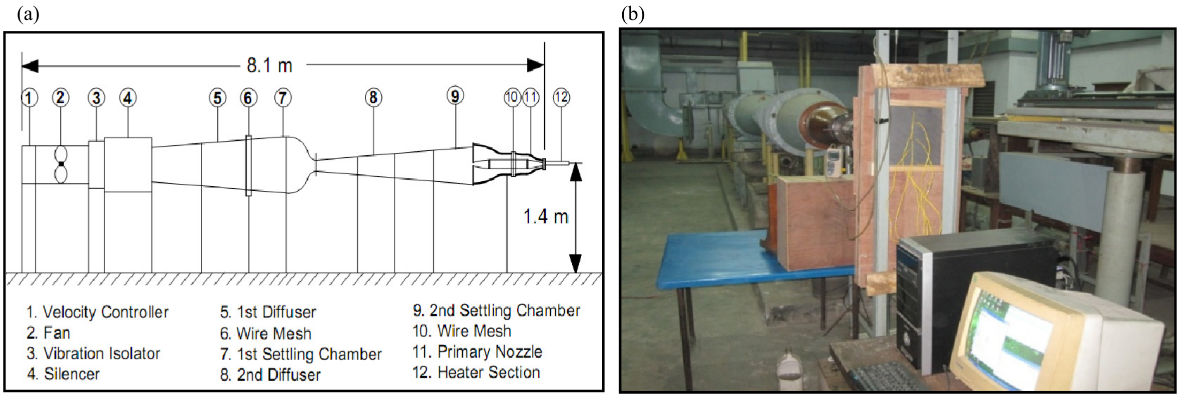

Fig. 1. (a) Schematic diagram of the wind tunnel, (b) Complete experimental setup with data acquisition system.

3. Experimental procedure

3.1. Methodology

The fan motors of the tunnel are initially started for a particular air flow with the help of butterfly valve and run about 15 minutes. The hot air jet is impinged on the base plate by removing the isolator and the thermo couple readings are recorded at the steady state condition. The same experiments are repeated for different conditions as given in Table -1. To cover all the experimental conditions, total 90 different experiments are performed yielding over 86,400 data points. To reach quasi-steady-state condition it takes about 60 minutes and then the computer controlled data acquisition system is allowed to run to record temperatures of all thermocouples in real time in every 1 sec. The test duration is limited by the semi-infinite solid assumption to 120 seconds. Experiments are performed for nozzle-to-plate separation (*l/d*) 2, 4, and 6. Eight pin type clips on all sides of the flat plate are employed to clamp the fabric with the base plate. In order to study the effects of air gap between fabric and flat plate, a solid wooden frame of 6 mm thick is placed beneath the flat plate. CF and FRF are then placed on the wooden frame and experiments are conducted.

Table 1: Experimental Conditions

Parameters	Value	Unit
Jet Velocity	12, 15, 19	m/s
Jet Temperature	115, 125	°C
Nozzle Diameter	25.4	mm
l/d	2, 4, 6	-
r/d	+ 4.5 ~ - 4.5	-

3.2. Mathematical equations

For the uniform initial temperature distribution, we could suddenly expose the surface to a constant surface heat flux (q_x) then the initial and boundary conditions provides -

$$T(x,0) = T_i$$

$$\frac{q_x}{A} = -K \frac{\partial T}{\partial x} \Big|_{x=0} \tag{1}$$

The solution for this case is

$$T_{(x,0)} - T_i = \frac{2q\sqrt{\alpha t/\pi}}{k} e^{\left(-\frac{x^2}{4\alpha t}\right)} - \frac{q_x}{k}\left(1 - erf\left(\frac{x}{2\sqrt{\alpha t}}\right)\right) \tag{2}$$

On the surface (x = 0) Eq. (2) reduces to,

$$T_{(t)} - T_i = \frac{2q\sqrt{\alpha t/\pi}}{k} \tag{3}$$

The local Nusselt number at each radial location, r/d, is derived from the surface heat flux history. Newton's law of cooling can be used to calculate the local heat transfer coefficient, h.

$$q_x = h(T_{jet} - T_i) \tag{4}$$

A major parameter for evaluating heat transfer coefficients is the Nusselt number,

$$Nu = \frac{h \cdot D}{K} \tag{5}$$

4. Results and discussion

4.1. Surface temperature (T_s) of the solid base plate and change of heat flux (q_s") at various radial locations

Fig. 2(a) represents time dependent surface temperature (T_s) variation on the solid massonite base plate (BP) is in contact with fire protective fabric (FPF), at nozzle-to-plate separation distance (*l/d*) = 6, jet temperature (T_{jet}) = 115 ^{o}C, and jet velocity (v_{jet}) = 12, for different radial locations (*r/d* = –4.5 ~ +4.5). It is observed that the maximum T_s is found at the stagnation point (*r/d* = 0). With the gradual increase of the radial distance (*r/d*) from the stagnation point to outer radial location (0 to ± 4.5) the surface temperatures are gradually decrease. In the same time, Fig. 2(b) represents change of heat flux ($q_s^{"}$) on BP is in contact with FPF, at *l/d* = 6, T_{jet} = 115 ^{o}C, and v_{jet} = 12, for *r/d* = –4.5 ~ +4.5. It is observed that, the maximum $q_s^{"}$ is found at *r/d* = 0. Both T_s and $q_s^{"}$ along with *r/d* are almost symmetric.

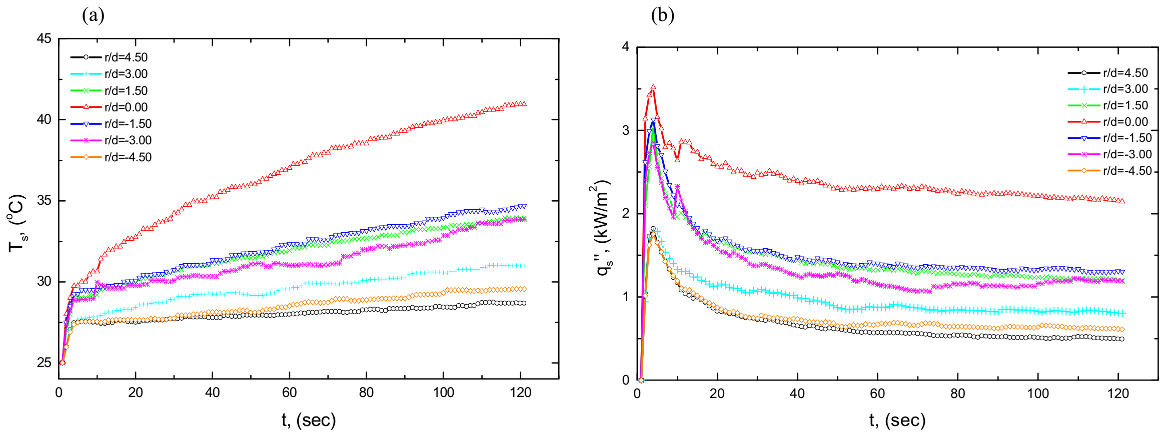

Fig. 2. Variation of surface (a) Temperature (T_s), (b) Heat flux ($q_s^{"}$) at *l/d* = 6; *r/d* = 0 ~ ± 4.5; T_{jet} = 115°C; v_{jet} = 12 m/s; FPF in contact with BP.

4.2. Effect of various nozzle-to-plate separation distance (l/d)of the jet on T_s and respective q_s"

Fig. 3(a) and 3(b) represent time dependent surface temperature (T_s) variation and change of surface heat flux ($q_s^{"}$) respectively of the base plate (BP) in contact CF, at stagnation point, *r/d* = 0, T_{jet} = 125 ^{o}C, v_{jet} = 19 m/s, for different nozzle-to-plate separation distance (*l/d*) = 2, 4, and 6. It is observed that the maximum T_s is found for *l/d* = 2 and decrease with the increase of nozzle-to-plate separation distance. These figures indicate, while the heat source is far from the solid surface, the surface temperature will be lower. For the long distance (*l/d* = 6), certain amount of heat of the jet will be transferred by convection and radiation; thus the temperature of the solid plate surface will be lower. That means, T_s values decrease for various nozzle-to-plate separation distance as per following order: *l/d* (2) > *l/d* (4) > *l/d* (6) > *l/d* (8) and so on.

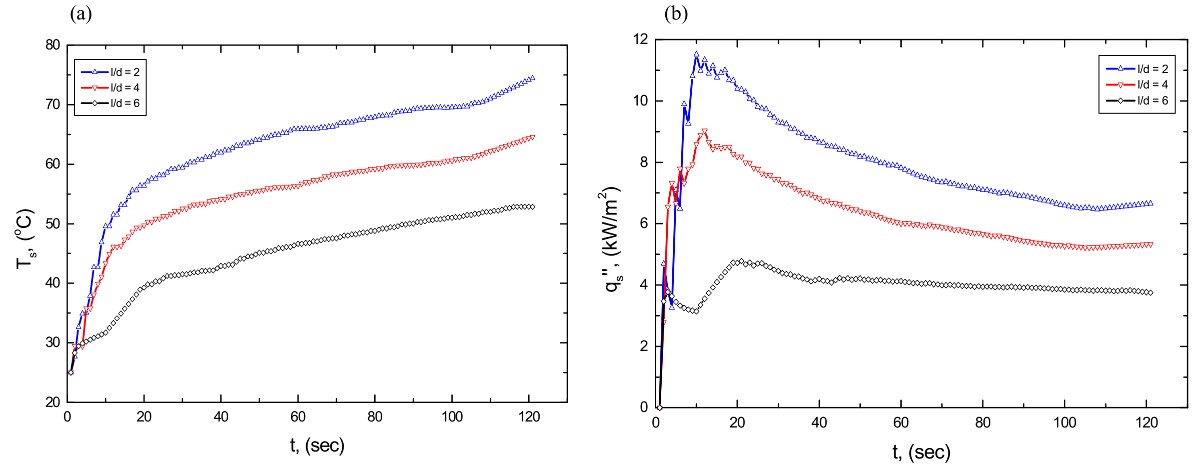

Fig. 3. Variation of surface (a) Temperature (T_s), (b) Heat flux (q_s'') at *l/d* = 2, 4, 6; *r/d* = 0; T_{jet} = 125 °C; v_{jet} = 19 m/s; CF in contact with BP.

4.3. Effect of jet velocities on T_s and respective q_s''

Fig. 4(a) and 4(b) represent time dependent surface temperature (T_s) variation and change of surface heat flux (q_s'') respectively of the BP alone, at the stagnation point (*r/d*) = 0, *l/d* = 4, T_{jet} = 125 °C, for different jet velocities, v_{jet} = 12, 15, and 19 m/s. It is observed that the maximum T_s and q_s'' are found at v_{jet} = 19 m/s and T_s, whilst q_s'' are decreasing with the decrease of jet velocity.

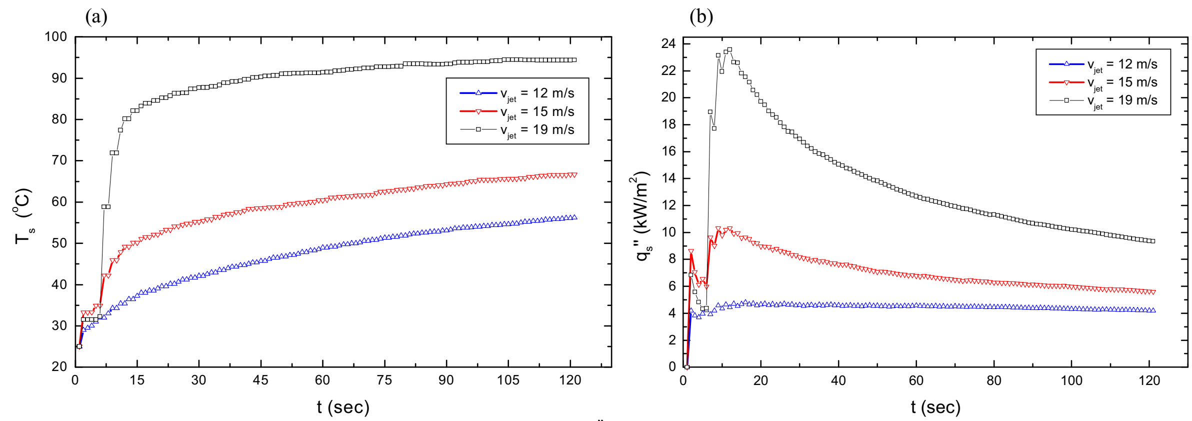

Fig. 4. Variation of surface (a) Temperature (T_s), (b) Heat flux (q_s'') at *l/d* = 4; T_{jet} = 125 °C; v_{jet} = 12, 15, 19 m/s; *r/d* = 0 of BP alone.

4.4. Effect of air gap between solid base to the fabric and in contact with the fabric

When a fire fighter wears fabric, there remain some places in contact with the skin to the fabric and due to the structure of the human body, rest of the places of the body create air gaps to the skin with the fabric. For this reason, in this study, experiments are conducted for fabric in contact with BP and 6 mm air gap with the BP. Fig. 5(a) and 5(b) represent T_s and q_s'' variation respectively of the base plate (BP) in contact with the CF and 6 mm air gap between base plate (BP) and cotton fabric (CF), at *r/d* = 0, *l/d* = 6, T_{jet} = 125 °C, and v_{jet} = 19 m/s. It is observed that the higher T_s are found for base plate (BP) in contact with the CF and the lower T_s are found for 6 mm air gap between base plate (BP) and cotton fabric (CF). As radiation heat transfer calculation has been neglected from the assumption of the present research, so the heat transfer value is speculated to be different from actual value.

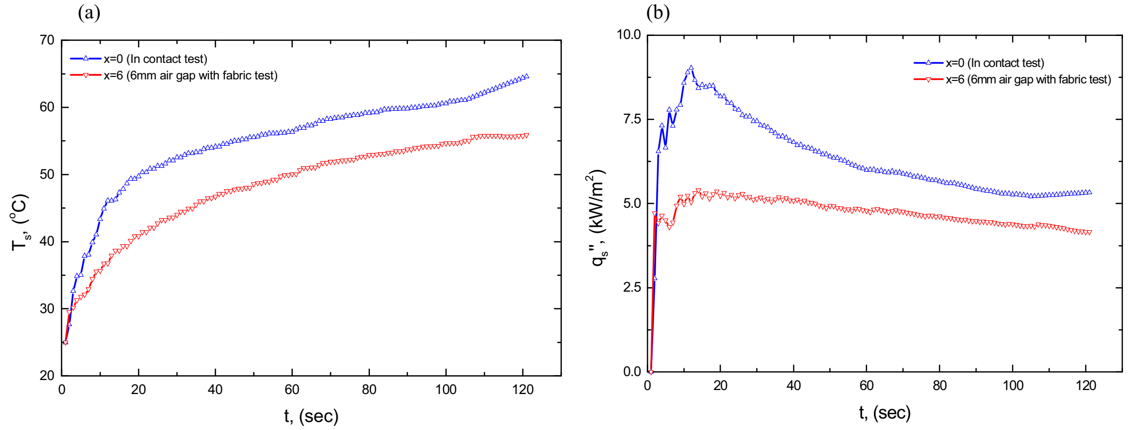

Fig. 5. Variation of surface (a) Temperature (T_s), (b) Heat flux (q_s'') at l/d = 6; T_{jet} = 125 °C; v_{jet} = 19 m/s; r/d = 0, BP in contact with CF, and 6 mm air gap between BF and CF.

4.5. Transient effect on Nusselt number (Nu)

The effect of transient heat transfer in terms of Nusselt number (*Nu*) with respect to radial distance from the stagnation point (*r/d*) has been shown in Fig. 6(a) and 6(b) for different time, t = 30, 60, 90, 120 seconds. It is found that the *Nu*, decreases with the increase of time (experimental or impinging time) for all type fabric conditions.

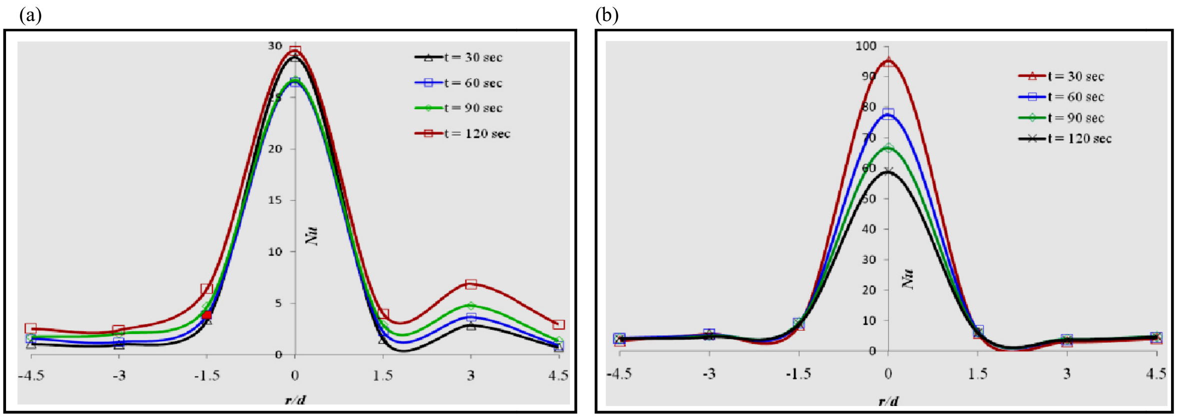

Fig. 6. Comparison of *Nu* at different t; r/d=0; T_{jet} = 125 °C; v_{jet} = 19 m/s; l/d = 6; (a) CF with BP, (b) BP alone.

The effect of transient heat transfer in terms of *Nu* with respect to radial distance from the stagnation point (*r/d*), and for different fabric conditions (FPF, CF, BP alone) has been shown in Fig. 7(a) - (d) in terms of t = 30, 60, 90, 120 seconds respectively. The highest value of *Nu* is found for base plate alone and lowest for FPF for all type fabric condition. The maximum value of *Nu* is found at r/d = 0. At r/d = 0, all the kinetic energy transformed into pressure energy. As a result the velocity air at the stagnation point is zero. But at stagnation point the temperature of the air is very high, thus the heat transfer coefficient is higher at stagnation point than the other radial position. So, the maximum pick of Nusselt number occurs at the stagnation point. After the stagnation point the velocity of air start to increase due to the pressure different between the surroundings and the stagnation point. But still the velocity of air is lower and the temperature of the jet decreases as the heat transferred to the base plate and the surroundings. For lower velocity and air temperature, the heat transfer coefficient also decreases, as well as *Nu*. With the increasing velocity the heat transfer coefficient of the air also increases. Although the temperature of the air is now very low then at the stagnation point, but due to the increase in velocity the Nusselt number is again increasing.

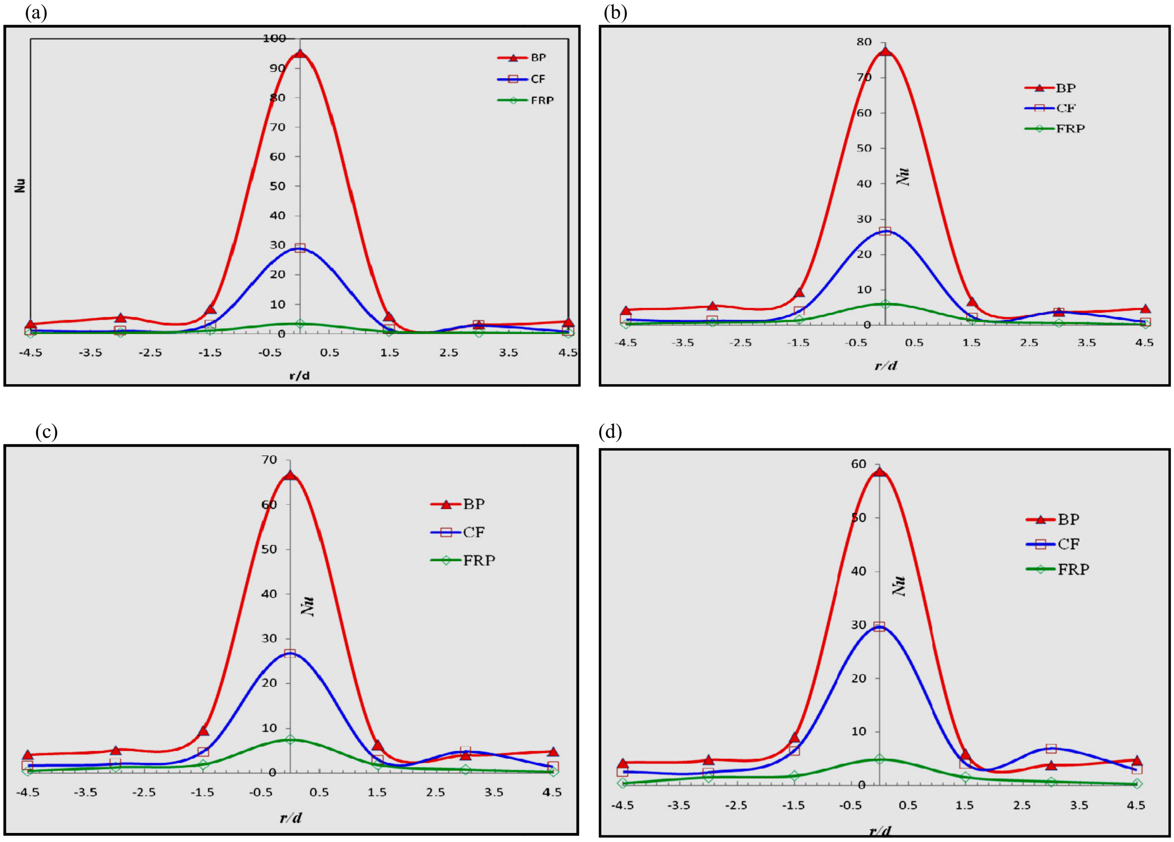

Fig. 7. Variation of *Nu* at different fabrics, at *r/d*=0; T_{jet} = 125 °C; v_{jet} = 19 m/s; *l/d* = 6; (a) t = 30, (b) t = 60, (c) t = 90, (d) t = 120 seconds.

4.6. Heat transfer comparison of the fabrics

Fig. 8(a) and 8(b) represents the surface temperature and change of heat flux for different fabric conditions, at the stagnation point (*r/d*), T_{jet} = 125 °C, v_{jet} = 19 m/s, *l/d* = 6 respectively. It is found that the lowest heat transfer occurred for FPF and the CF shows poor performance to resist heat transfer through the fabric.

(a) (b)

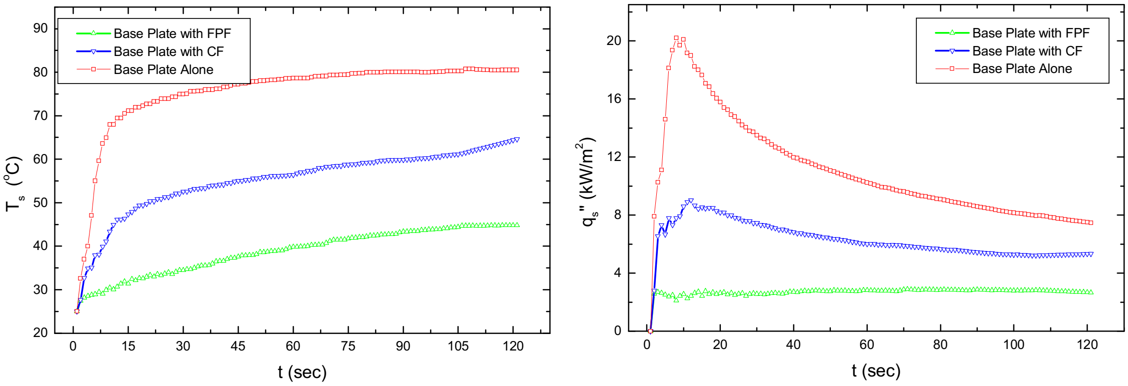

Fig. 8. Variation of surface (a) Temperature (T_s), (b) Heat flux (q_s'') at T_{jet} = 125 °C; v_{jet} = 19 m/s; l/d = 6; r/d = 0 for different fabric conditions.

5. Conclusions

An experimental setup is built to measure the thermal response of the fire retardant fabric system. The jet velocities are varied 12, 15, and 19 ms^{-1} respectively and temperatures are 115 and 125 °C respectively. Two permeable fabrics (Kevlar® 49 and cotton fabric) are considered. From the local heat transfer history, it is found that the surface heat flux (q_s'') is dependent on time, radial location (r/d) or nozzle to plate separation distance (l/d), and jet velocity (v_{jet}). The experimental results represent that the maximum heat transfer is occurred for base plate alone at 125 °C. From the experimental results, it can be concluded that the model can be used to determine various fabric/clothing design parameters for an optimum thermal protection and to estimate skin burn coupled with a fabric system under the jet impingement heating condition. It is also found that the surface heat flux history is dependent on the radial location (r/d) distances. The surface temperature and heat flux are almost symmetric along radial location and maximum values are found at the jet stagnation point (r/d = 0) for all cases. Initially, the heat transfer occurs as in transient mode and the surface temperature increases very rapidly and after a certain time, the surface heat transfer becomes steady. With the time increment, the rates of heat transfer to the base plate from the jet decreases. The fire resistance capacity of the cotton fabric (CF) is found to very poor comparing to the fire protective fabric (FPF). The FRF Kevlar® shows excellent performance to protect the heat transfer through the fabric. As the FRF Kevlar® has the potential to protect the heat transfer through the fabric, so it can be used as suit for the fire fighters at a certain condition of temperature and time.

References

[1] Islam, A.K.M. N., Study of heat transfer of a solid with protective fabric under hot air jet impingement, *M.Sc. thesis*, Department of mechanical engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, (2013) 1-127.

[2] Perry, K. P., Heat transfer by convection from a hot gas jet to a plane surface, *proceeding of mechanical engineering inst.*, Vol. 168 (1954) 775 – 784.

[3] Chen, N. Y., Transient heat and moisture transfer through thermally irradiated cloth, *Ph.D. thesis*, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 1959.

[4] NASA CB65579, LR 18900, A transient heat transfer and thermodynamic analysis of the apollo service module propulsion system, *Summary report*, Manned spacecraft center, Primary propulsion branch, Houston, Texas (1965) 1 – 15.

[5] Gardon, R. and Akfirat, J. C., The role of turbulence in determining the heat transfer characteristics of impinging jets, *International journal of heat and mass transfer*, Vol. 8 (1965) 1261 – 1272.

[6] Mohanty, A. K. and Tawfek, A. A., Heat transfer due to a round jet impinging normal to a flat surface, *International jomurnal of heat and mass transfer*, Vol. 36 (1993) 1639 – 1647.

[7] Goldstein, R. J., Behbahani, A. I., and Heppelmann, K. K., Stream wise distribution of the recovery factor and the local heat transfer coefficient to an impinging circular air jet, *International journal of heat and mass transfer,* Vol. 29 (1986) 1227 – 1235.

[8] Ukponmwan, J. O., The thermal insulation properties of fabrics, *Textile progress*, Vol. 24, Number 4 (1993)

[9] Torvi, D. A., A finite element model of heat transfer in skin subjected to a flash fire, *M.Sc. thesis*, Department of mechanical engineering, University of Alberta, Edmonton, Alberta, Canada (1992).

[10] Backer, S., et al., Textile fabric flammability, *The MIT Press*, Cambridge, Massachusetts, 1976.

[11] Stoll, A. M. and Chianta, M. A., Method and rating system for evaluation of thermal protection, *Aerospace medicine*, Vol. 40, (November 1969) 1232 – 1238.

[12] Stoll, A. M. and Weaver, J. A., Mathematical model of skin exposed to thermal radiation, *Aerospace Medicine*, Vol. 40, (1969) 24 – 30.

[13] Torvi, D. A., Heat transfer in thin fibrous materials under high heat flux conditions, *Ph.D. thesis*, Department of mechanical engineering, University of Alberta, Edmonton, Alberta, Canada (1997) 1 – 277.

[14] Torvi, D. A., and Sawcyn, C. M. J., Flow visualization in air spaces between protective fabrics and sensors in protective clothing tests, Department of mechanical engineering, University of Saskatchewan, Saskatoon, Alberta, Canada (2004) 1 - 6.

[15] Anguiano, R. M., Transient heat transfer through thin fibrous layer, *M.Sc. thesis*, Department of mechanical engineering, University of Alberta, Emonton, Albarta, Canada (2006) 1-92

[16] Islam, MA, Rezwan, AA, Hossain, S, and Islam, AKM N, Study of transient heat transfer of a solid with protective fabric under hot air jet impingement, *Proc. Int. Conf. on mechanical engineering (ICME2011),* Dhaka, Bangladesh (December 2011), ICME11-TH-042, 1-6.

[17] Hasan, M. N., Experimental study of flow characteristics in the near field of a thermally stratified co-axial free jet, *M.Sc. thesis*, Department of mechanical engineering, Bangladesh University Of Engineering and Technology, Dhaka, Bangladesh, (2008) 1-159.

[18] ASTM F2703-08, Standard test method for unsteady-state heat transfer evaluation of flame resistant materials for clothing with burn injury prediction.